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Energy Procedia 23 (2012) 333 – 342

Energy Procedia

The 6th Trondheim CCS Conference

Cost Estimation of Fossil Power Plants with Carbon Dioxide Capture and Storage

Diana Voll[1a], Dr. Arnim Wauschkuhn[a], Rupert Hartel[b], Dr. Massimo Genoese[b], Prof. Dr. Wolf Fichtner[b]

[a]*EnBW Energie Baden-Württemberg AG, 76131 Karlsruhe, Germany*

[b]*Chair of Energy Economics, Karlsruhe Insitute of Technology,76131 Karlsruhe, Germany*

Abstract

CCS will play an important role in reducing greenhouse gas emissions in order to limit global warming to 2° Celsius by 2050. Amongst other things, both the costs and the technologies associated with CCS are subject to uncertainties. Cost estimations in the literature vary significantly. Some analyses provide cost estimation for CCS as a generic value, giving only a few distinctive technical options and only a few attempts to investigate the costs separately for each technology. The objective of this paper is therefore to analyze the cost spectrum for CCS provided by different studies and to determine realistic cost estimations for carbon dioxide capture and storage, as well as to investigate the impact of costs on the economic maturity of CCS. Results show that costs of CCS vary significantly along the CCS process chain. Furthermore, it becomes apparent that further efforts need to be taken, both in technology development and in terms of the willingness of an economy to pay high prices for mitigating CO_2 emissions, before CCS may be referred to as economic feasible.

Keywords: CCS technologies, electricity generating costs, investment

[1] Corresponding author. Tel.: +49-721-63-23204; fax: +49-721-63-12939.

E-mail address: d.voll@enbw.com

 doi:10.1016/j.egypro.2012.06.038

1. Introduction

Due to climate change the worldwide consensus is to make every effort to limit the global average increasing temperature to 2°C compared to pre-industrial times (2°C target) [1]. The raising CO_2 concentration in the atmosphere is regarded as a major cause of the increasing temperature. To achieve the 2°C target, it is therefore necessary to reduce the worldwide greenhouse gas emissions. In addition to that the high, and still growing, worldwide energy demand needs to be met. To guarantee a sustainable and responsible energy supply the following three objectives have to be met:

- First an environmentally sound energy generation, aiming for an electricity generation with an increasing share of renewable energies but besides reducing CO_2 emissions also setting emission standards for other pollutants such as NO_x, SO_x and dust.
- Second the objective of high efficiency, on one hand applied to both household customers and industry but also by using state-of-the-art technology for power plants, on the other hand also economic efficiency providing an affordable and economic sustainable energy supply.
- The third objective is the security of energy supply by modernizing and extending the grid and using complementary sources of energy generation to be able to accept the challenge of increasing volatility due to the growing percentage of renewable energies in the generation mix.

Carbon Capture and Storage (CCS) can be regarded as a technology whose core target it is to mitigate CO_2 emissions, but that is also able to contribute to the other two objectives of a sustainable and responsible energy supply. If applied to fossil power plants, CCS can contribute to security of energy supply by providing environmentally sound, central and base-load (stable) electricity. With a restricted CO_2 emission cap and increasing European Allowance Units of one ton of CO_2 (EUA) prices CCS also has the potential to be one of the most economic efficient ways of producing stable and environmentally sound energy.

2. Techno-economic maturity and other challenges of CCS by means of commercial deployment

CCS is one option that will play an important role to mitigate the worldwide CO_2 emissions. Although by means of commercial deployment of the technology major challenges exist that need to be tackled. The four major challenges are social acceptance, a legal and regulatory framework, the management of the CCS value chain and the techno-economic maturity.

Social acceptance is a challenge that is being faced worldwide, especially when industrial-scale onshore CO_2 storage sites and/or pipelines for CO_2 transportation will be or are being investigated. Lacking storage sites and possibilities to transport CO_2 due to social resistance are major drivers to postpone the commercial deployment of the CCS technology. Therefore the lack of social acceptance has to be faced by joint efforts of industries, research institutes and governments with the aim to prove the technology and show the impact and benefit of its worldwide application.

A legal and regulatory framework is indispensable for a commercial deployment of CCS. International federations such as the European Union and others bring a national legislation to regulate topics like the assumption of risk for CO_2 storage on the way. Nevertheless, a variety of topics still needs to be covered, such as allowing offshore CO_2 transportation as regulated within the OSPAR convention and the London Protocol or the detailed integration of CCS into the European Emissions Trading Scheme (EU ETS).

With the application of the CCS technology a new process respectively value chain is created. One major challenge is the management of this value chain, facing open questions such as the ownership of the CO_2 along the value chain or the suitability of each link of the value chain into a user's existing business model (operator vs. user).

The fourth challenge is the techno-economic maturity, which can only be achieved when the following aspects and their interactions are well balanced. Techno-economic maturity on the one hand is the focusing on a variety of technical options such as the three capture technologies post-combustion capture, pre-combustion capture and oxyfuel-combustion, but also on the level of deployment of these technical options. Costs differ significantly in regards to a 1st-of-a-kind vs. a nth-of-a-kind-plant (cf. [2]) but other issues like the management of CCS interfaces, such as the purity of the CO_2 stream, might also add up costs by means of the application of extra cleaning equipment. Techno-economic maturity on the other hand is the attainment of economic maturity. Economic maturity can only be achieved by finding the right balance between costs and benefits. Costs are being regarded as the sum of capital expenditure (CAPEX) and operational expenditure (OPEX), including market models such as EU ETS and their influence on the costs like the price for CO_2 allowances (EUA). Benefits can be differentiated into global, social and monetary benefits.

3. Cost estimation of fossil power plants with CCS

For energy utilities it is essential to know the costs of fossil power plants with CCS, as considerations on mid- and long-term power generation start nowadays and costs are a main driver to estimate the future competitive positions of fuels within a generation mix. One reason for considerations at early stages is the construction period of a fossil power plant with a duration of approximately eight to ten years, consisting of a planning phase of two to three years, a permitting phase of one to two years and a phase where the power plant is realized / erected within a time ranging from three to five years. Additionally, fossil power plants are operated during a time of up to 40 years, so decisions on the erection of fossil power plants nowadays might or probably will have an influence on the power generation in the 2040s or even 2050s.

When estimating cost of fossil power plants with CCS two challenges have to be faced. First noticeable variations exist between primary offers and /or cost estimates for the construction of a plant and the actual costs at the execution of a project. This is due to the fact that charges for risks and profits will be added by suppliers, but as experiences show also results in uncertainties about cost estimations in early stages and probably also for more mature situations. Secondly the challenge of acquiring the necessary data has to be tackled. The approach of the cost estimation of this paper is described within the following chapter.

3.1. Approach of cost estimation

Thirteen of the most relevant studies [2]-[14] dealing with the cost of CCS are identified, analyzed and compared. When comparing cost figures from different studies many factors have to be considered. The studies have to be differentiated by country, currency and publishing year. The CCS technologies in the power industry can be distinguished in pre-, post- and oxy-fuel-combustion, and each of these technologies can be combined with the fossil fuels natural gas, lignite and hard coal. The cost estimation of CCS plants does not only depend on the general technology-fuel combination, but also on the reference power plant without capture (the so-called state-of-the-art power plant). Furthermore, assumptions made about capture rates, efficiency losses due to the capture of CO_2 and the development of technical improvements[2] play an important role. CCS clearly is a very heterogeneous technology field and a comparison of cost estimations is not easily conductible.

The above-mentioned aspects influence the value of the cost figures (of the specific studies). For a comparison the influence of origin and publication year has to be considered, which is defined as “harmonization”. Therefore costs are converted to the defined base year 2009 and inflation and the development of the national industry are taken into account. The American and European plant capital cost index [15] is used to reflect the development of the power plant costs. Since the CO_2-capture is a chemical process the chemical engineering plant cost index is used to harmonize the costs that arise for the CO_2-capture, if the plant costs for this additional application are stated separately.

After the harmonization of the given values a more detailed examination is conducted. For this reason a detailed categorization according to technology and fuel is carried out. The values for each category are

[2]Depending whether the cost estimation of the study refers to a first of a kind or a nth of a kind plant.

shown as band width, covering values such as specific investments, additional production, CO_2 avoidance cost and the cost for transport and storage. The range of those values is analyzed for several years. This quantitative analysis again shows the variation of the cost estimation, i.e. the investment costs for coal fired power plants vary by 30-40 %. Further assumptions are shown in the following chapters and figures.

3.2. Range of specific cost for CO_2-capture, -transportation and -storage

Figure 1 shows a comparison of mean values of specific costs of fossil power plants with and without CO_2-capture distinguished by fuel and capture technology. The examined values illustrate the mean value of specific investment costs of a variety of studies for the base year 2030. Already by the sole application of CO_2-capture to the power plant, a significant increase of the specific investment in € per kW gross electrical power ranging from +30% to +70% has been determined, while costs for transport and storage will add even further up to this. As a more detailed example: Specific costs of a supercritical hard-coal fired power plant currently under construction (such as RDK 8[3]) are about 1,200 €/kW, whereas the mean value of the seven examined studies investigating costs of hard-coal fired power plants with post-combustion capture is about 1,700 €/kW for a nth-of-a-kind project in 2030. This equals an increase of costs of about 40%.

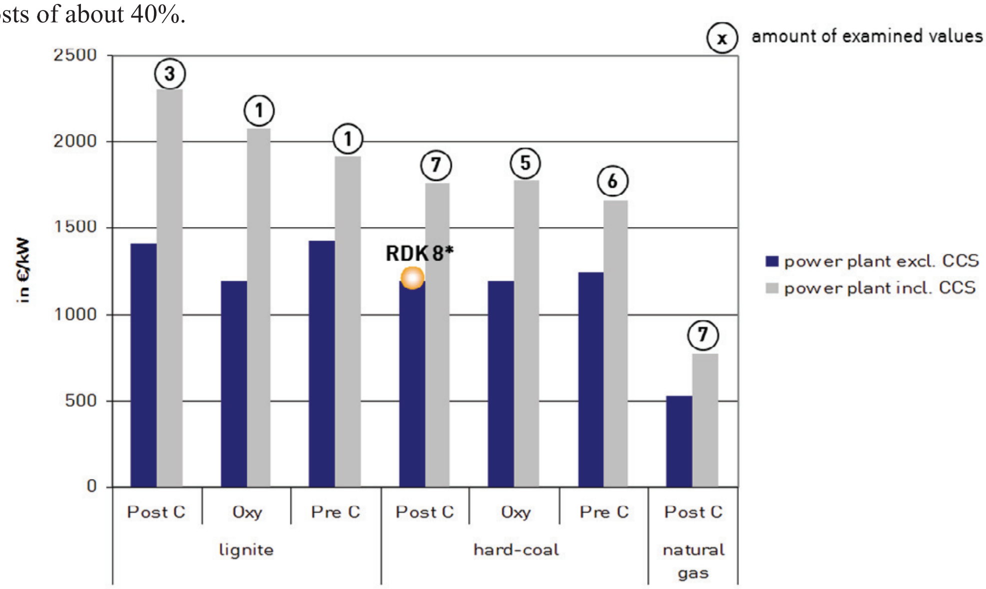

Fig. 1. Specific costs of fossil power plants with and without CO_2-Capture (2030, base year: 2009)

[3] RDK 8 = Rheinhafendampfkraftwerk unit 8 is a 912 $MW_{gros,el}$ hard-coal fired power plant currently under construction at EnBW (Energie Baden-Württemberg AG) site in Karlsruhe, Germany.

Whereas Figure 1 only shows the mean value of the investigated studies, the bandwidth of costs for each of the examined fuel and capture technologies, if examined by more than one study, are as follows: post-combustion capture and lignite 2062 €/kW – 2621 €/kW, post-combustion capture and hard coal 1268 €/kW – 2393 €/kW, oxy-combustion with hard coal 1459 €/kW – 2258 €/kW, pre combustion and hard coal 1232 €/kW – 2060 €/kW and post-combustion and natural gas 804 €/kW – 1044 €/kW.

The costs of transportation and storage of CO_2 are very much depending on the location of the power plant, the amount of CO_2 as well as on the option that is been used for transport and storage. Besides the variety of those options distinguishing between transport by pipeline onshore, pipeline offshore, ship, truck or rail and between storage in saline aquifers onshore /offshore and depleted gas / oil fields onshore / offshore also the amount of transported and stored CO_2 plays a significant role, when investigating costs.

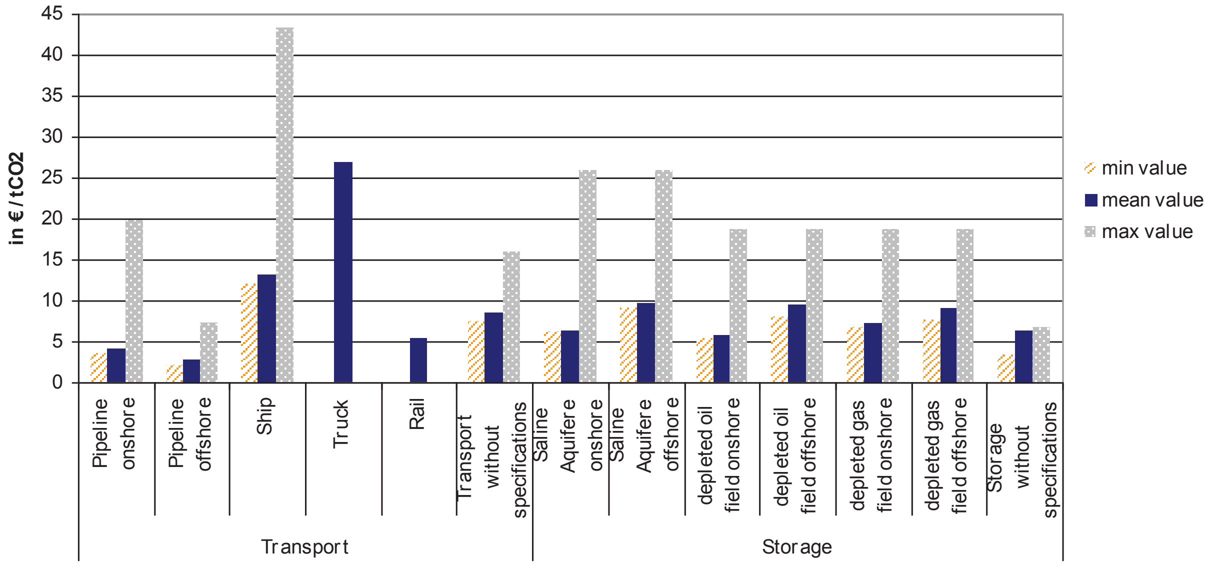

Fig. 2. Range of costs of CO_2-transport and –storage (2030)

Figure 2 is a comparison of the costs in €/tCO_2 for various transport and storage options. Those costs vary significantly both for transportation of CO_2, between 2€/tCO_2 (min value transport via pipeline) and 43€/tCO_2 (max value transport via ship), and for storage of CO_2, between 5€/tCO_2 (min value storage in depleted oil field onshore) and 26€/tCO_2 (storage in saline aquifer offshore / onshore).

Due to the significant variation of costs regarding all parts of the CCS value chain, it is complicated to make conclusions about the future costs of fossil power plants with CCS as well as conclusions about when the technology will be economically mature. One major indicator for the economic maturity of the technology is the price of CO_2 as displayed by the EUA price or similar instruments (taxes etc.). A first approach on how abatement costs of fossil power plants with CCS might look like in 2030 as a bandwidth of costs but also for a more specific project will be discussed within the following chapter.

3.3. CO_2-abatement costs of fossil power plants with CCS

Abatement costs are additional costs arising from the use of a technology with low greenhouse gas intensity compared to the prevailing state of the art. The CO_2-abatement costs can be regarded as the value of reducing CO_2-emissions. To achieve economic maturity of CCS, an economy or other market participants have to be willing to pay a price for the benefit of reducing CO_2, e.g. by buying emission allowances, which at minimum covers the abatement cost. These CO_2-abatement costs are an equation of levelised costs of electricity (LCOE) and the intensity of emissions incl. a mean value of 13€/tCO_2 for transportation and storage:

$$abatement\ costs = \frac{LCOE_{CCS} - LCOE_{ref}}{IE_{ref} - IE_{CCS}}$$

With: LCOE – Levelised Costs of Electricity with CCS and for the reference case without CCS

IE – Intensity of Emissions with CCS and for the reference case without CCS[4]

As illustrated in Figure 3, even if examined per fuel the estimations of abatement costs differ considerably. Whereas abatement costs of lignite fired power plants with CCS differ between 41€/tCO_2 – 110€/tCO_2, abatement costs of hard-coal fired power plants with CCS vary from 39€/tCO_2 – 100€/tCO_2 and the abatement costs of natural gas fired power plants with CCS differ from 96€/tCO_2 to 121€/tCO_2.

[4] Difference of Intensity of Emissions (also specific emissions of power plant) of reference plant and Intensity of Emissions with CCS is not to be mixed up with capture rate. Due to higher energy consumption of plant with CO_2-capture the Intensity of Emissions of plant with CCS are higher than reductions in tCO_2/MWh with CCS in comparison to the reference case.

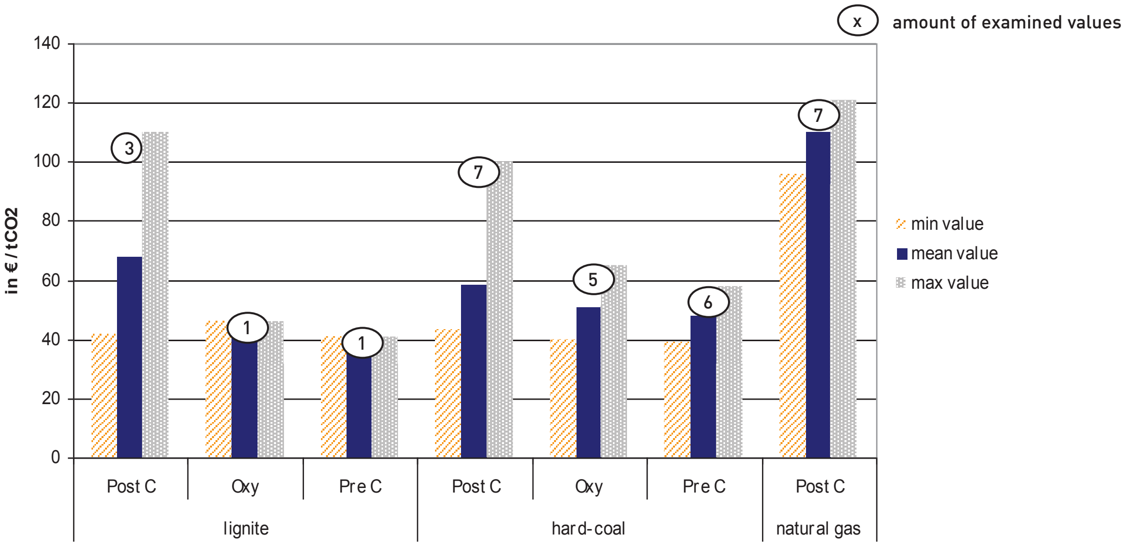

Fig. 3. CO_2-abatement costs of CCS (2030)

Figure 4 shows an example of CO_2 abatement costs based on a specific – hypothetical – project. Basis for the calculation of the abatement costs is a hard-coal fired power plant with an applied post-combustion capture. The power plant is located at a coastal site with connection to a storage site in a depleted gas field offshore. The transportation is executed via a pipeline with a length of approx. 200 km.

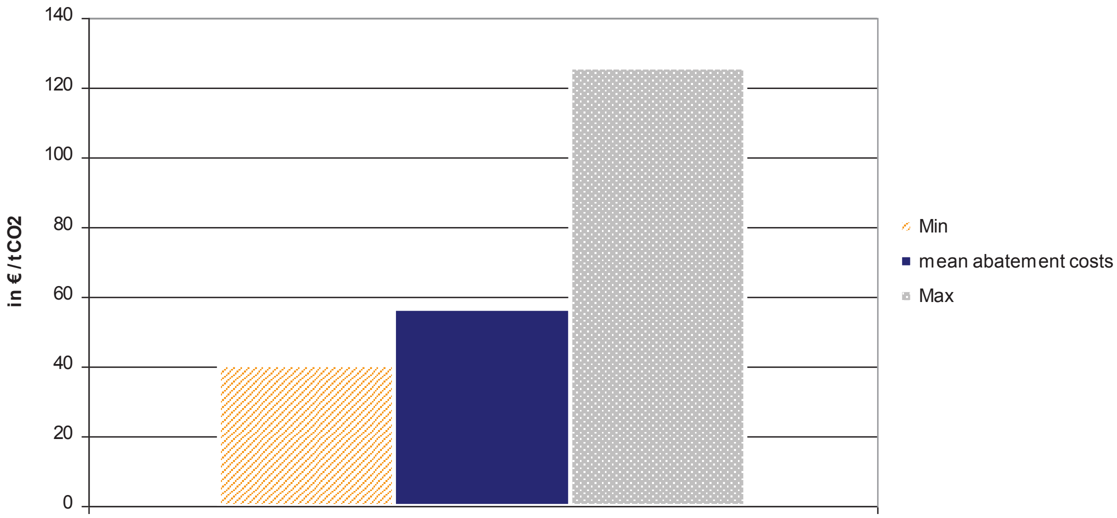

Fig. 4. Example of CO_2 abatement costs based on the application of CCS at a hard-coal fired power plant (2030)

As for economic maturity of CCS market participants have to be willing to pay a price for reducing CO_2 emissions, a comparison of the current EUA-price with the calculated abatement costs has to be carried out. With abatement costs ranging from 40 €/tCO_2 to 126 €/tCO_2 with a mean value of 57 €/tCO_2 for the sole project shown in Figure 4, the price of EUA should be at minimum 40€/tCO_2. With current EUA prices of around 15 €/tCO_2 even a n^{th}-of-a-kind consideration doesn't allow the conclusion of economic maturity.

4. Conclusion

Existing studies mostly cover only costs for new build CCS power plants. Considering legislation like the EU directive [16], however, which demands that current new build power plants at least reserve a plot for a later installation of CCS, further investigations on the costs and impacts of retrofitting CCS at existing power plants should be conducted by all involved parties. Nevertheless, calculating the general economics of retrofit is very challenging, since in the case of a retrofit with CCS technology the costs are very dependent on the location, technology and other boundary conditions of the existing power plant.

Furthermore, the probability that further costs will accrue in the future is rather high. Those costs might occur through any public dues levied, for instance as part of the draft version of the German CCS legislation [17] §42, stating that dues can be levied by federal states. Other cost will be incurred as a result of the contribution for the maintenance of the storage sites after closure. To use the example of the German CCS legislation again, it is stated in §32 that this contribution shall be 3% of the EUA annual price for the stored amount of CO_2.

Power plants with CCS will become more cost-intensive concerning the investment as costs increase for the application of the CCS components. Regarding the market-related (Merit Order) variable operating costs for fuel and CO_2 allowances, power plants with CCS will be less cost-intensive than power plants without CCS, since up to 90% of the CO_2 allowances can be cut by safely capturing and storing CO_2. One question that can be raised regarding the shifted cost-intensity is whether current market models such as the EU ETS are still suitable for power generation with CCS. If the EU ETS remains the preferred instrument within the European market model in the long-term, EUA prices need to be high enough to not only cover the increased CAPEX but also the increased OPEX occurring through the reduction in efficiency, as well as higher operational and maintenance costs for the capture plant.

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